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Laboratory studies on the effect of external electric fields and discharges on charge transfer during ice-hail collision

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Abstract : Laboratory experiments have been carried out in a walk-in cold room to investigate the effect of uniform and radial electric fields and electrical discharges on charge transfer during collision between ice crystal and graupel (soft-hail). It has been found from these experiments that the average size of crystal decreases with the increasing electric field. However, when discharges are applied to the cloud the ice crystal size is larger. It is also seen that the charge transfer value is always high for low electric field and less for high electric field. The charge transfer values after a discharge has taken place in the cloud are higher. It is also observed that the ratio of ice crystal to water droplet is an important parameter for thunderstorm electrification. If the ratio is high then charge transfer values are less and if the ratio (<1) is small, charge transfer values are more.

Keywords : Thunderstorm electrification, charge transfer, electric field, electric discharge.

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1. Introduction

The study of thunderstorm and its charging mechanism is important because a significant fraction of the Earth's rainfall in temperate climates comes from electrified clouds, and it is possible that the precipitation processes and charging processes in thunderclouds are influenced by electric fields and electrical discharges. Laboratory and field experiments have confirmed that the electric fields of the order of 10^5 V m^{-1} are present in natural thunderclouds [1,2].

It is widely accepted that the development of the electric field in thundercloud is associated with a non-inductive charging mechanism which involves rebounding collisions between ice crystal and graupel (soft-hail). Many laboratory experiments have been performed under simulated thunderstorm condition [3–7] to measure the charging of graupel. The pioneering work of Reynolds *et al* [8] determined that riming graupel pellets charge negatively at temperatures around –25°C during collisions with ice crystals in the presence of super cooled droplets.

Scott and Levin [9] noted the negative charging during the collision of graupel and ice crystals taking place in a positive electric potential gradient. Aufdermaur and Johnson [10] reported negative charging when graupel and drops interacted in electric fields. They also noted that significant charge separation occurred only in the presence of an electric field. Latham and Mason [11] found that there is no significant charging when ice crystals collide with graupel in an electric field. Latham *et al* [12] suggested that charge transfer between cloud particles in an electric field would probably be much more important for ice crystals or snowflakes. Since the collection efficiency increases rapidly as electric field is increased, the process of charge transfer between ice crystals in an electric field of about 200 V cm^{-1} could be of much greater importance in generating charges in thunderstorm.

Takahashi [3] reported that the graupel size increases with the electric field strength in the clouds. Thus, the

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electric field does not appear to play a dominant role in charge separation, even if the cloud is highly electrified because of the relatively large fall-speed of graupel. Crowther and Saunders [13] reported that ice crystals falling in high electric fields might be prone to break-up by the action of the field upon their induced charges. Evans [14] also suggested that even in less intense uniform electric field experienced in natural cloud, there may be sufficient fragmentation to account for the multiplication of ice crystals.

The literature survey on charge transfer during collisions between ice crystal and graupel in the presence of external electric field shows that the results are conflicting [3,9–11]. In order to clarify the results, the present laboratory experiments were designed and performed. Experiments were carried out to investigate the magnitude and sign of charge that is transferred to the rimed target during collision with ice crystal in the presence of external electric field and discharge. The vapor supply was not cut off during the experiments and therefore the target was riming during the collision.

2. Experimental Methodology

Experiments were carried out in a cloud chamber kept in a walk-in cold room, with the lowest attainable temperature of −30°C. The chamber consists of a spherical glass flask of 20-liter capacity with extended cylindrical limbs at top and bottom. Figure 1 shows the experimental setup inside the cold room. A small-extended glass tube on the lower

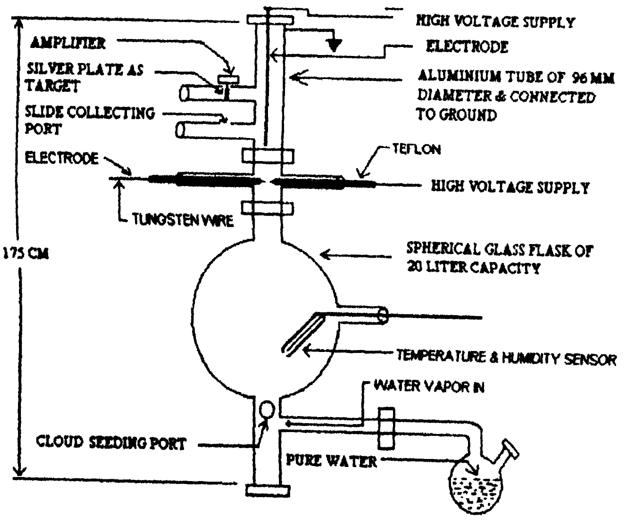


Figure 1. Schematic representation of experimental arrangement for discharge experiment. When external electric fields are applied to the clouds, the electrodes for discharge experiments, are removed and one aluminum rod electrode (44.5 cm long and 0.66 cm diameter) is introduced at the center of the cloud chamber from the top.

limb is used for introducing water vapor into the chamber. There are two extended tubes (upper one is made of aluminum and lower one is made of glass) on the upper limb with the separation of 10 cm. The diameter (inner) of both the tubes is 2.7 cm. Inside the upper extended tube (aluminum tube) a target, 18 × 4 mm of silver plate, is kept vertically and directly connected to the input of the charge amplifier. To prevent oxide formation on the surface of the silver target it is chemically cleaned very frequently and calibration runs of charge transfer are carried out. The lower extended tube (glass tube) is used for collecting the crystals on the formvar coated microscope slide and is of the same size as that of the target. Both tubes are connected to suction pump through a glass valve.

Pure water is heated at a controlled rate and vapor is allowed to come into the chamber from the bottom to form a cloud of super cooled droplets and vapor. There is no leakage of air in and out of the chamber. Temperature and humidity of the cloud are measured and recorded in real time on a computer-based data acquisition system. A metal rod dipped in liquid nitrogen is momentarily introduced into the cloud chamber to initiate the ice crystal formation inside the cloud by homogeneous freezing of super cooled droplets. Vapor supply to the chamber was maintained at the same rate throughout the experimental run. The cloud temperatures varied from −9°C to −14°C. Before starting the charge transfer experiment, suction pump is used to suck the mixed phase cloud through the side extended tube to make rime (soft-hail/graupel) on the silver target. Cloud of super cooled droplets and ice crystals is drawn through the tubes with constant speed of 2.9 m s^{-1}.

A hot film conical probe (TSI, Model 1054 A) was used to determine the flow speed exactly at the silver target. A hot film measures the air velocity by sensing changes in heat transfer from a small, electrically-heated sensor (wire or thin film) exposed to the fluid under study. The heated sensor is held at a constant temperature using an electronic control circuit. The cooling effect resulting from the fluid flowing past the sensor is compensated for by increasing the current flow to the sensor. This calibration was carried out at the Indian Institute of Tropical Meteorology (IITM) and was done at normal room temperature and not at the temperatures at which charge transfer experiments were carried out. The voltage on the suction pump was fixed and the corresponding air velocity was noted using the TSI hot film probe and is accurate to +/−0.5%.

Inside the upper tube the ice crystals collide with rimed target and rebound from the target. During the collisions, ice crystals transfer charge to the rimed target and then these transferred charges are measured by a charge amplifier. Microscope slide coated with a solution of chloroform and formvar is kept vertically inside the side extended (lower) tube to collect the ice crystals which impact on it, for further analysis. Once the ice crystal numbers are very few in the cloud, this mixed phase cloud is drawn momentarily through both extended tubes.

Using the formvar replication technique, super cooled water droplets from the cloud is collected for a definite time (t). From the microscopic image, these droplets as seen within the microscope's circular view area (A) were counted (N) and their average radius (r) was determined. Droplet spectral data was corrected using appropriate values of collection efficiency [15]. As the droplets fall through the cloud, they cover a distance of $U \times t$ where U is the downward droplet velocity [16] given by $U = k_1 \times r^2$ ($k_1 = 1.19 \times 10^6$ cm^{-1} s^{-1}). Therefore essentially the droplets collected in our experiments had been occupying the cylindrical volume of height $U \times t$ and area of cross section A in the cloud. The Liquid Water Content (LWC) of the cloud given by the total volume of all the water droplets collected, divided by the volume of the cylinder is

$$\text{LWC} = \{(4/3) \times \pi \times r^3 \times N \times \rho\} \,/\, \{(U \times t) \times A\}$$

where ρ is the density of water.

The values of ice crystal size and liquid water content keep changing continuously and therefore the values taken are that at the time of charge transfer and these are found from the samples collected from the formvar coated microscope slides. The impact speed is kept constant and does not vary as long as the voltage to the suction pump is steady.

2.1. Charge transfer experiments in presence of electric field :

In these experiments high voltages (400 V, 500 V, 1000 V, and 2000 V) were applied to the central electrode which was an aluminum rod of 0.66 cm diameter and 44.5 cm long to produce a uniform and radial electric field inside the cloud. The experimental arrangement is shown in Figure 1. The electric fields were applied throughout the experimental run and ice crystals were allowed to grow in presence of electric field. The maximum size of crystal is found to be140 μm and average size of the crystal is 50 μm during these experiments.

2.2. Charge transfer experiments after an electrical discharge in the cloud :

For these experiments two tungsten electrodes made of 1.0 mm diameter are inserted in the chamber (Figure 1) from the side extended tubes and the separation between two end points is 0.8 cm. A high voltage was applied for a moment between these two electrodes to produce electrical discharge inside the cloud comprising of super cooled drops and ice crystals. This process is repeated four times in a time interval of 15 seconds during one experimental run so that enough ions are released into the cloud. During the time of electrical discharge, there is cracking noise and is loud enough to be heard outside the cold room. The maximum size of crystal is found to be150 μm and average size of the crystal is 50 μm during these experiments.

3. Results

Charge transfer values for the above series of experiments have been measured during collisions between ice crystal and graupel (soft-hail). The sign of the charge that is transferred to the graupel is always positive in the temperature range –9°C to –14°C. It is also seen that the charge transfer value, from a single collision, decreases with increasing ambient electric field in the cloud. Ice crystal size also decreases with increasing ambient electric field. However, in case of discharge in the cloud, it is seen that the charge transfer values are high.

Figures 2 to 5 show charge transfer values as functions of ice crystal size when different values of electric potential are applied to the cloud. Figure 6 shows charge

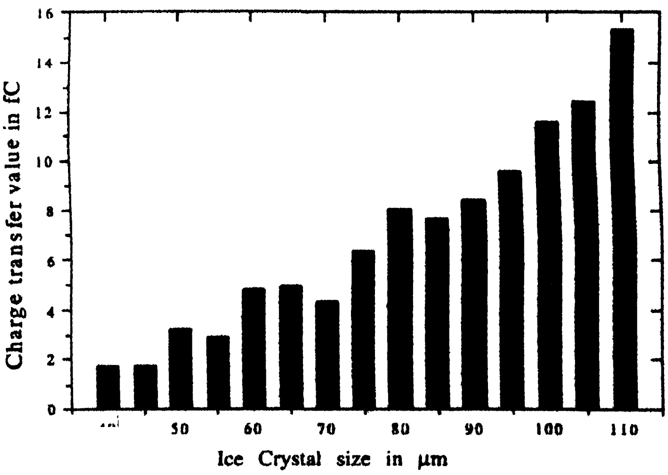


Figure 2. Shows charge transfer values plotted against ice crystal size when 400 V was applied to the cloud.

transfer values as functions of ice crystal size when electric discharges are applied to the cloud. It is observed that charge transfer values are dependent on external electric field. If the electric field is high then the charge transfer value is low. However, when discharges are applied to the cloud then the charge transfer values have high.

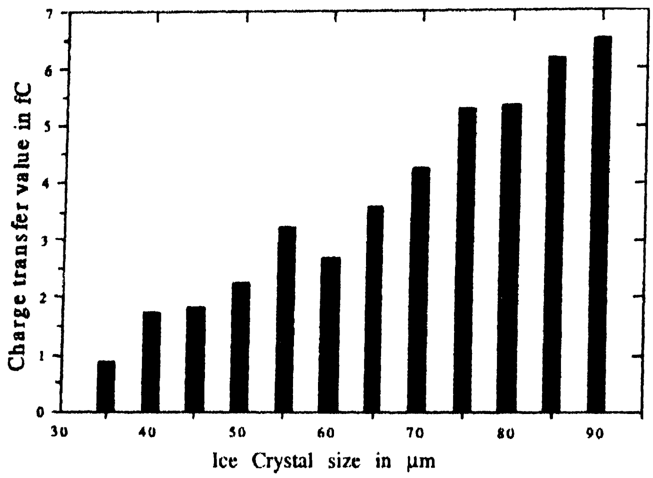


Figure 3. Same as Figure 2 when 500 V was applied to the cloud.

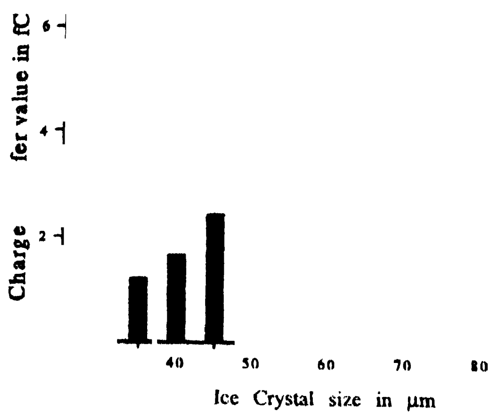


Figure 4. Same as Figure 2 when 1000 V was applied to the cloud.

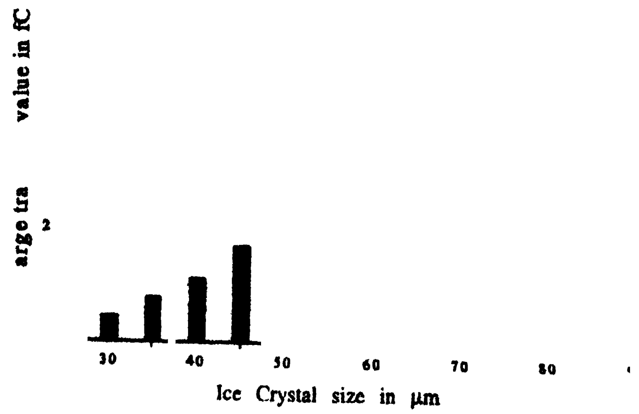


Figure 5. Same as Figure 2 when 2000 V was applied to the cloud.

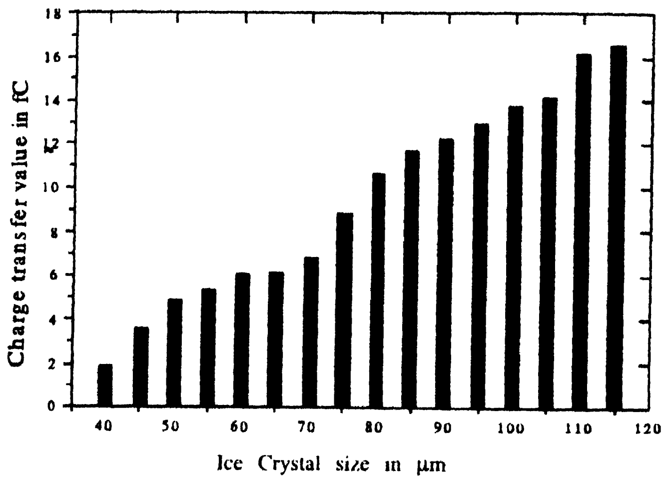


Figure 6. Shows charge transfer values plotted against ice crystal size when electrical discharges were applied to the cloud.

Figures 7 to 10 show charge transfer values as a functions of ice crystal size and liquid water content (LWC) when crystals collided and bounced off a rimed target in the presence of ambient electric field which was produced by applying potentials of 400 V, 500 V, 1000 V and 2000 V respectively. It is seen from these figures that the charge transfer value decreases with increasing of external electric field. These figures also show that the charge transfer value is also dependent upon the LWC in the cloud. It is also seen that the maximum size of the

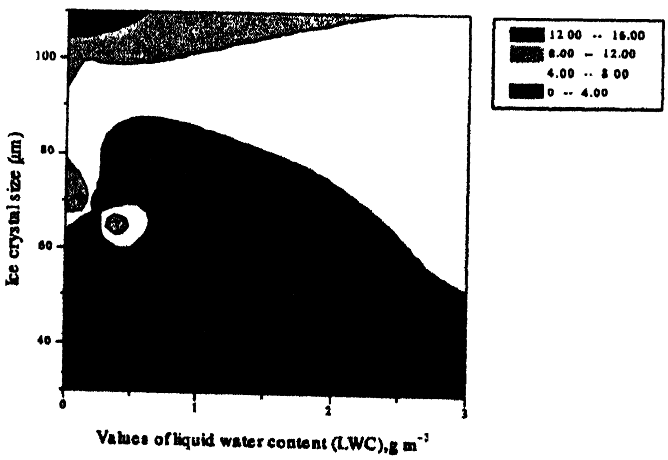


Figure 7. Charge transfer values plotted against LWC and crystal size when 400 V was applied to produce in the cloud.

crystal observed in the cloud decreases with increasing ambient electric field. Figure 11 shows that charge transfer values as functions of ice crystal size and liquid water content (LWC) when discharges are applied to the cloud.

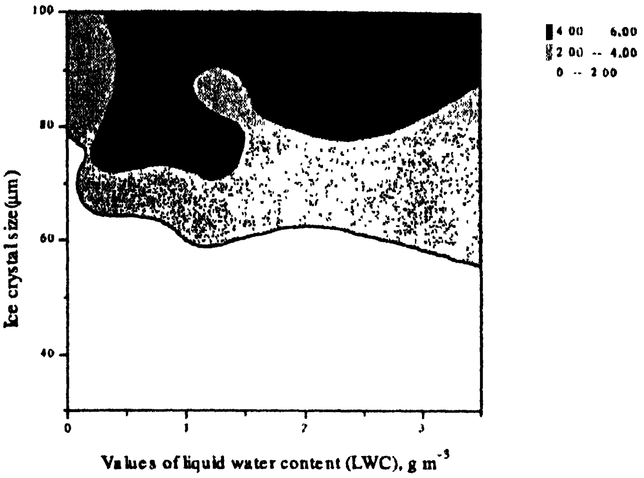


Figure 8. Same as Figure 7 when 500 V was applied in the cloud.

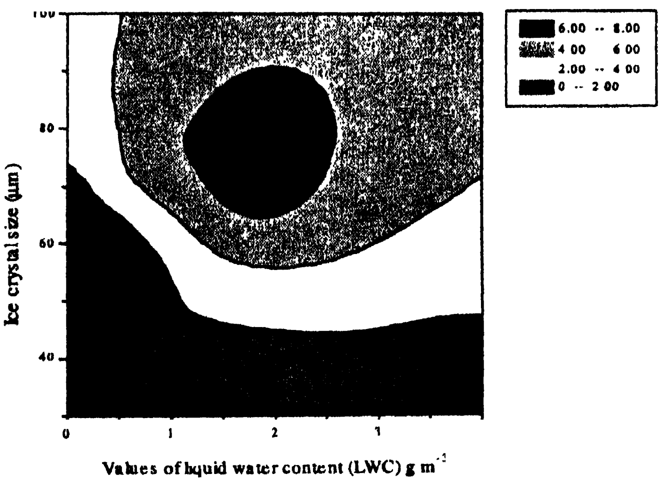


Figure 9. Same as Figure 7 when 1000 V was applied in the cloud

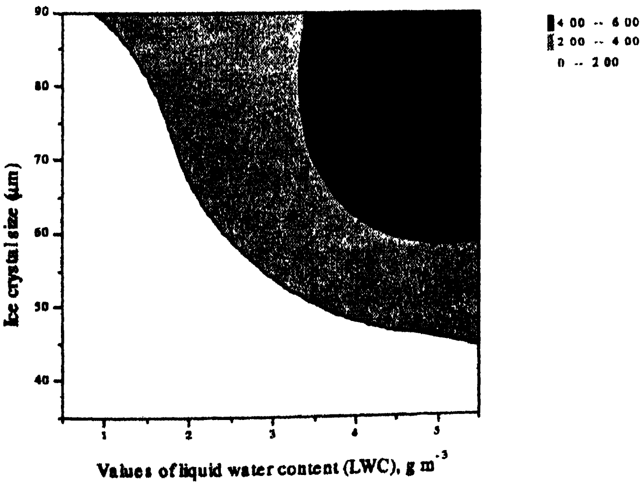


Figure 10. Same as Figure 7 when 2000 V was applied in the cloud.

It is found that charge transfer values are higher and crystal size are also larger when discharges are applied to the cloud.

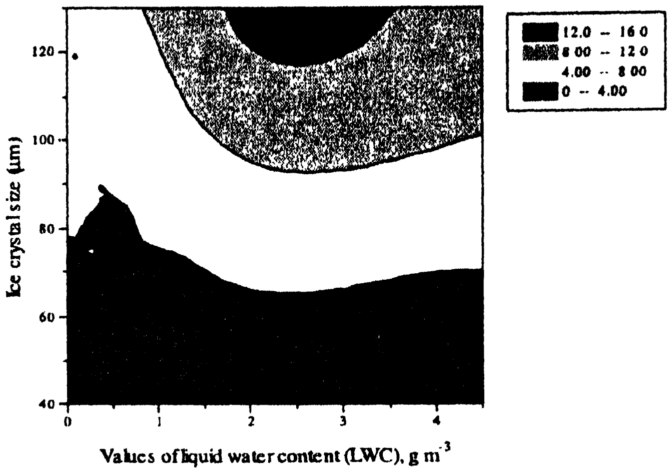
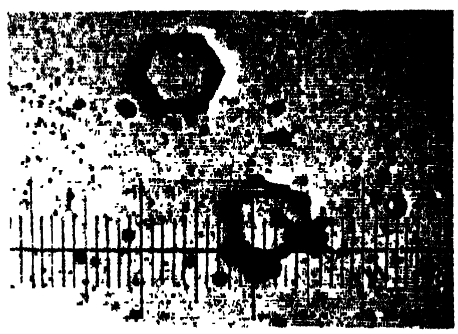
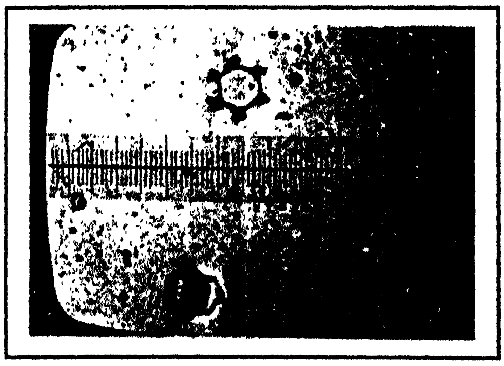


Figure 11. Charge transfer values plotted against LWC and crystal size when electrical discharges was applied in the cloud

Figure 12 shows the photomicrographs of hexagonal plate like ice crystals collected from a laboratory cloud

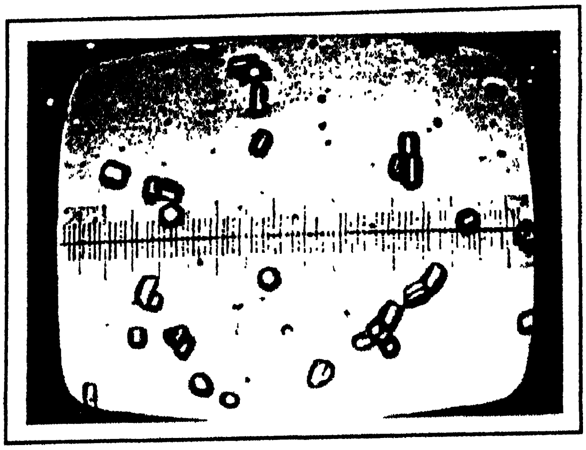


(a)



(b)

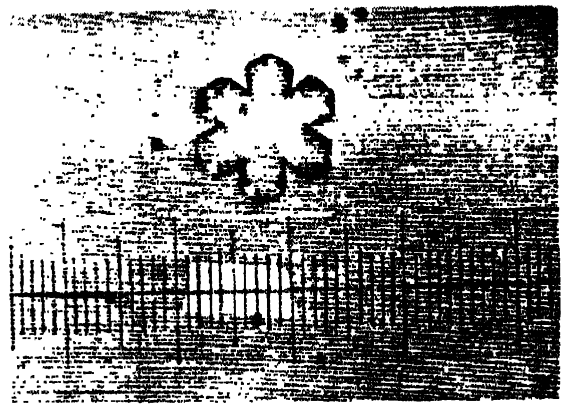
Figure 12. Photomicrographs of ice crystals collected from pure water cloud where the applied voltage was 400 V. (a) Crystal habit is hexagonal plate and the average size is 70 μm (1 scale division =10 μm). and (b) Crystal habit is hexagonal plate and the average size is 90 μm (1 scale division =10 μm).



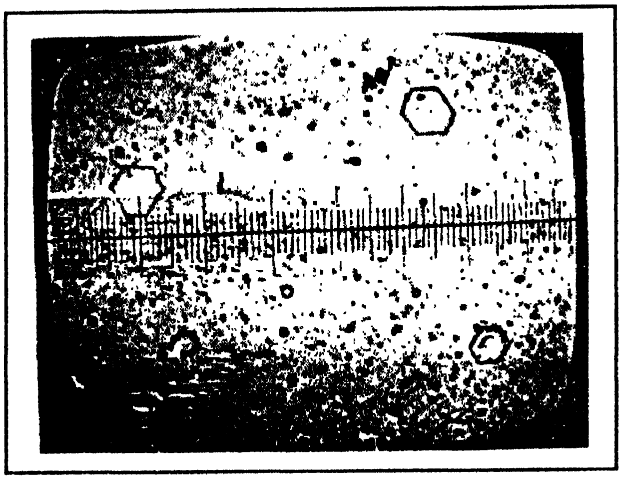
(a)

(b)

Figure 13. Photomicrographs of ice crystals collected from pure water cloud where the applied voltage was 2000 V. (a) Crystal habit is column like and hexagonal plate, and the average size is 35 μm (1 scale division =10 μm). and (b) Crystal habit is hexagonal plate and the average size is 40 μm. (1 scale division =10 μm)



(a)



(b)

Figure 14. Photomicrographs of ice crystals collected from pure water cloud when electric discharges were applied. (a) Crystal habit is hexagonal plate and size is 100 μm (1 scale division =10 μm). and (b) Crystal habit is hexagonal plate and the average size is 90 μm (1 scale division =10 μm)

when 400 volts were applied to the cloud. The average size of the plates in Figure 12(a) is 70 μm and the average size of plates in Figure 12(b) is 90 μm and the size of supercooled water droplets is 12 μm. Figure 13 shows the photomicrographs of hexagonal plate and column like ice crystals collected when 2000 volts were applied to the cloud. The average size of the columns in Figure 13(a) is 35 μm and the average size of plates in Figure 13(b) is 40 μm and the size of supercooled water droplets is 10 μm.

Figure 14 shows the photomicrographs of plate like ice crystals collected from cloud when discharges were applied to the cloud. The size of the hexagonal plate in Figure 14(a) is 100 μm and the average size of hexagonal plates in Figure 14(b) is 90 μm.

4. Discussions

In these experiments, we have observed that charge transfer values from a single collision between ice crystal and graupel are always high when ambient electric field is low and also when the charge transfer has taken place after an electric discharge has occurred in the cloud. The sign of the charge that is transferred to the graupel, is always positive in the temperature range –9°C to –14°C. It is seen that the liquid water content is an important parameter in charge transfer mechanism and in our experiments it varied from 0.1 to 5.5 g m^{-3}. Charge transfer values increased with increase of liquid water content in the cloud.

It has also been observed that if the voltage applied to produce ambient field is high (1000 V or 2000 V), the average size of the ice crystal is smaller and charge transfer values are also low. Crowther and Saunders [13] suggested that ice crystals falling in high electric fields might be prone to break-up by the action of the field upon their induced charges. The resulting ice fragments will act as sites for the deposition of more vapor and the growth of further ice crystals. Crowther and Saunders [17] also reported that if two ice crystals passing closely to each other in an electric field of 10^5 V m^{-1} or more than those ice crystals are involved in fragmentation. They suggested that fragmentation of ice crystals falling in an electric field is caused by the interaction of both the total and induced charges on the crystal when they are separated by small distances. Jayaratne *et al* [6] measured that the magnitude of the charge per event as a function of crystal size. They also reported that the charge from a single collision for a 125 μm size crystal was +10 fC at –6°C for an impact speed of 3.0 m s^{-1}. They also observed that the positive charging at temperatures warmer than –18°C and negative charging at colder temperatures. Keith and Saunders [18] performed charge transfer experiments at –15°C with dendrites of size 800 μm and an impact speed of 3 m s^{-1}. The charge per collision for this size was +220 fC. Saunders *et al.* [19] reported that for a crystal of 100 μm size at temperature -24°C and an impact speed of 5 m s^{-1}, the charge transfer value was –7.5 fC from a single collision. Aufdermaur and Johnson [10] found that when frozen water drops collided with a pellet at 10 m s^{-1} large charges were separated independently of an applied electric field of 50 kV m^{-1}. Here the field is not expected to have any effect because the relaxation time for conduction in ice is about 10 m s, much longer than the time of contact.

In our experiments where high electric fields were present in the clouds, the average crystal size was smaller and it is possible that the collision from these smaller ice crystals resulted in lower values of charge transfer. In experiments with electric discharges, the production of ions could be very high and it is likely that these ions can attach with ice crystals and finally during collision it could be transferred to the graupel resulting in higher value of charge transfer.

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